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19. Abstract

The research in constrained optimization supported at Rice by this grant has been significant and extensive. This work involves the development and analysis of novel practical approaches to the classical problem of minimizing a real-valued nonlinear function of several, perhaps many, real variables subject to nonlinear equality constraints on the variables and the problem of finding a zero of a system of nonlinear equations. This work is now being continued under AFOSR support.

Included in this research is the continued development of the successful Celis-Dennis-Tapia trust-region approach to equality constrained optimization. A challenging global convergence analysis for this method has been successfully concluded in a Ph.D. thesis written by M. El Alem.

Another successful project was the development of a BFGS secant method theory for the equality constrained optimization problem and the corresponding local convergence theory. The standard BFGS secant theory requires the matrix that is being approximated to be positive definite on the entire space. In constrained optimization the matrix that is being approximated is only positive definite on a proper subspace. The proper formulation of the BFGS secant method for constrained optimization had previously eluded researchers for many years. This theory was tested and the method modified in work by Tapia in conjunction with Y. Zhang, an AFOSR postdoc on this grant, and Professor Richard Byrd of the University of Colorado, Boulder whose sabbatical at Rice was supported by AFOSR through his contract at UC, Boulder.

Another successful project was the development of structured secant methods and the corresponding local convergence theory. In a structured secant method the matrix that is being approximated has the property that a part can be readily calculated; hence only the remaining part need be approximated. While the literature abounds with algorithms which use the philosophy of structure, the development of a convergence theory had been done only in a few special cases. We developed a theory for the entire convex class.

Another successful project was the development of a method for arbitrary norm trust-region methods for nonlinear equations and the corresponding global convergence theory. A special case of this theory is the well known Levenberg-Marquardt 2-norm trust-region theory for nonlinear equations.

A part of the research performed at Rice involved the safeguarding of Hessian approximations in secant methods for unconstrained optimization. Numerical experimentation demonstrated that this safeguarding was quite helpful. This work constituted the PhD thesis of Richard Carter whose implementations were employed successfully by AFOSR researchers under the direction of Professor Tom Banks.

Research IN Constrained Optimization

Considerable steps were taken in understanding and extending the now famous Karmarkar projective scaling transformation and corresponding theory for linear programming.

We also developed and analyzed an interesting and useful parallel direct search method for unconstrained optimization. This work was the PhD thesis of Virginia Torczon. The method is more robust than the well-known Nelder-Mead simplex method and just as insensitive to noise in the function values.

Papers Completed

1. (J.E. Dennis and T. Steihaug) On the Successive Projections Approach to Least-Squares Problems, *SIAM J. on Numerical Analysis*, 23 (1986), pp.717-733.
2. (J.E. Dennis with Kathryn Turner) Generalized Conjugate Directions, *Journal for Linear Algebra and Applications*, 88/89 (1987), pp.187-209.
3. (J.E. Dennis with Daniel J. Woods) Optimization on Microcomputers: The Nelder-Mead Simplex Algorithm, in *New Computing Environments: Microcomputers in Large-Scale Computing*, edited by Arthur Wouk, SIAM, Philadelphia, (1987), pp.116-122.
4. (J.E. Dennis with M. Morshedi and Kathryn Turner) A Variable-Metric Variant of the Karmarkar Algorithm for Linear Programming, *Math. Prog.* 39 (1987), pp.1-20.
5. (J.E. Dennis with Guangye Li) A Hybrid Algorithm for Solving Sparse Nonlinear Systems of Equations, *Math. Comp.* 50 (1988), pp.155-166.
6. (J.E. Dennis with Daniel J. Woods) Curve Tailoring with Interactive Computer Graphics, *Appl. Math. Letters*, 1 (1988), pp.41-44.
7. (J.E. Dennis with Sheng Songbai and Phuong Vu) A Memoryless Augmented Gauss-Newton Method for Nonlinear Least Squares, *Journal of Computational Mathematics*, 6 (1988), pp.355-375.
8. (J.E. Dennis, H.J. Martinez and R.A. Tapia) A Convergence Theory for the Structured BFGS Secant Method with an Application to Nonlinear Least Squares, *J.O.T.A.* 61 (1989), pp.159-177.
9. (J.E. Dennis with R. B. Schnabel) A View of Unconstrained Optimization, invited paper in *Optimization, Handbooks in Operations Research and Management Science, Vol 1.*, edited by G.L. Nemhauser, A.H.G. Rinnooy Kan, and M.J. Todd, North Holland, Amsterdam, pp.1-72.



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10. (R.A. Tapia and Y. Zhang), A fast optimal basis identification technique for interior point linear programming methods, submitted to *Linear Algebra and its Applications*, 1989.
11. (R.A. Tapia and Y. Zhang), A cubically convergent algorithm for locating optimal vertices in linear programming, submitted to *J. Optimization Theory and Applications*, 1989.
12. (R. Byrd, R.A. Tapia, Y. Zhang), An SQP structured augmented Lagrangian BFGS secant algorithm for constrained optimization, to be submitted to *SIAM J. on Optimization*, 1989.
13. (Y. Zhang with R. P. Tewarson), Quasi-Newton algorithms with updates from the pre-convex part of Broyden's family, *IMA J. Numer. Anal.*, 8, 487-509, 1988.
14. (Y. Zhang) Computing a Celis-Dennis-Tapia trust region step for equality constrained optimization, submitted to *Mathematical Programming*, 1989.
15. (R.A. Tapia, R. Fontecilla and T. Steihaug), A Convergence Theory for a Class of Quasi-Newton Methods for Constrained Optimization, *SIAM J. Numer. Anal.* 24 (1987), 1133-1151.
16. (R.A. Tapia and J. Stoer), On the Characterization of q -superlinear Convergence of Quasi-Newton Methods for Constrained Optimization, *Math. Comp.* 49 (1987), 581-584.
17. (R.A. Tapia and David Whitley) The projected Newton Method has Order $1 + \sqrt{2}$ for the Symmetric Eigenvalue Problem, *SIAM J. Numer. Anal.* 25 (1988), 1376-1382.
18. (R.A. Tapia), On Secant Updates for use in General Constrained Optimization, *Math. Comp.* 51 (1988), 181-202.
19. (R.A. Tapia), The Local Convergence of Sequential Quadratic Programming Methods, MaSc 87-4, submitted for publication (with J. Stoer).
20. (R.A. Tapia), Karmarkar as a Classical Method, MaSc TR 87-7, submitted for publication (with M. Morshedi).
21. (R.A. Tapia and M. El Hallabi) A Global Convergence Theory for Arbitrary Norm Trust-Region Methods for Nonlinear Equations, MaSc TR 87-25, submitted for publication.

Participating Professionals

J.E. Dennis, Jr.	Professor of Mathematical Sciences
R.A. Tapia	Professor of Mathematical Sciences
Y. Zhang	Post-doctoral Research Associate
R. Byrd	Visiting Associate Professor (Colorado)
P. Tarazaga	Visiting Scholar (Argentina)

Advanced Degrees Awarded

The following students were awarded or are expecting the Ph.D. degree in Mathematical Sciences under the direction of Professors Dennis and/or Tapia and received at least partial support from this grant.

M.R. Celis (1985). A trust region method for constrained optimization.

Daniel J. Woods (1985). An interactive approach for solving multi-objective optimization problems.

Edward J. Dean (1985). A model trust region modification of inexact Newton's methods for nonlinear two point boundary value problems.

Teresa Parks (1985). Reducible nonlinear programming problems.

Guangyi Li (1986). Algorithms for solving sparse nonlinear systems of equations.

Richard Carter (1986). Multi-model algorithms for optimization.

Mohammed El Hallabi (1987). A global convergence theory for arbitrary norm trust region methods for nonlinear equations.

Kathryn Turner (1987). A variable metric variant of the Karmarkar algorithm for linear programming.

Jershan Chiang (1988). Convergence rates for the variable and the multiplier in Successive Quadratic Programming methods.

Mahmoud El Alem (1988). A global convergence theory for a class of trust region algorithms for constrained optimization.

Hector J. Martinez R. (1988). Local and Superlinear convergence of structured secant methods from the convex class.

Sho-Bai Li (1989). A general convergence theory for trust-region methods.

Virginia Torczon (1989). Parallel optimization by searches on simplex edges.

Catherine Samuelsen (1989 expected). An extension of the Kar-mar-kar algorithm to nonlinear programming problems.

Karen Williamson (1990 expected). A convenient trust region algorithm for equality constrained nonlinear programming.